Whole Body Vibration Exposure for MH-60S Pilots

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Abstract

Pilots of the MH-60S helicopter are exposed to continuous whole body vibration (WBV). Pilot fatigue is a growing operational concern due to the increased frequency of extended durations of missions (6-8+hours) in support of Operations Iraqi Freedom and Enduring Freedom. Endurance aspects of the currently used rotary wing seating systems were not optimized for the longer missions and wide range of pilot anthropometric measurements, which is now typical of naval aviation. The current seating systems were designed primarily to meet crashworthiness requirements, not for the wide range of pilot anthropometry or to mitigate WBV. Albeit, an issue, pilot fatigue and reduced mission effectiveness are also critical concerns.

Current Hazard Reports (HAZREP) indicated that pain in both pilots' legs and backs begin 2 to 4 hours into the flight and increase with time. Situational awareness also decreases with an increase in flight duration due to the constant distraction of pilots shifting in their seats while trying to get comfortable. Froom (1987) reported a dose-response relationship between the length of military helicopter flights and back discomfort. He also concluded that this pain is typically dull, over the lower back, and its prevalence and intensity are dependent on the total flight hours of exposure.

This study evaluated WBV produced in the pilot seating systems onboard the MH-60S. The purpose of the study was to test and compare the effectiveness of three different seat cushions, the current seat cushion versus two anti-vibration seat cushions A and B. The three seat cushions were measured for acceleration levels averaged over five-minute intervals using a triaxial seat pad accelerometer. The recordings were completed for several round-trip straight and level flights. A frequency analysis from 0-80 hertz (Hz) was conducted on all acceleration measurements to determine the dominant axis and frequency of the pilots' vibration exposure. The results were then compared to the applicable Threshold Limit Values (TLVs) established by the American Conference of Governmental Industrial Hygienists (ACGIH) [1] to determine the MH-60S pilots' permissible exposure time for all seat cushions.

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The results of the study showed that for all three seat cushions the vibration levels of the z-axis at 16 Hz had the shortest allowable exposure duration, according to the ACGIH TLVs. In the z-axis at 16 Hz, the MH-60S's current seat cushion almost pierced the 4-hour exposure time limit curve and anti-vibration seat cushion B pierced the 8-hour exposure time limit curve. The anti-vibration seat cushion A reached the 16-hour exposure time limit. Anti-vibration seat cushion A outperformed the current seat cushion and anti-vibration seat cushion B by exhibiting significantly reduced vibration levels.

Using the criteria set forth in Military Standard 882 and DoDI 5000.2, the current seat cushion and anti-vibration seat cushion B may result in a mishap severity category III or IV. This mishap category would be consistent with IIIC, which requires Program Executive Officer approval, or IVB/C, which requires Program Manager approval for associated human and programmatic risks. These guidelines should be incorporated into the design and acquisition process and should be integrated within Capability Development Documents (CDDs) and Capability Production Documents (CPDs) that provide the basis for future requirements, funding and follow-on contract documents.

Introduction

WBV affects approximately 6 million workers in the United States who regularly operate trucks, buses, heavy equipment, forklifts, helicopters, fixed wing aircraft, small marine craft, and ships. Continuous exposure to excessive levels of vibration can cause irreversible damage to the human body. Health and safety concerns include back injuries (degenerative disc disease), fatigue, and impaired performance [9]. Evolving military strategy and operational demands create increased duration of air support missions, particularly for rotary wing aircraft.

A review of the literature revealed that helicopter pilots have a prevailing amount of back pain due to the required posture and/or WBV from the aircraft [2]. Some reports have identified the pain as extreme localized pain at the lumbar region and/or buttocks [5], [6], [18], which can increase the potential of nerve compression [6], [16]. Additionally, helicopter pilots have reported chronic back pain and sought medical treatment [2], even though they risk their flight status being revoked. In 1984, Aviation Space Environmental Medicine published an article, which documented that when compared to jet pilots, rotary wing pilots have an increased incidence of lumbar abnormalities [7]. Furthermore, back pain becomes chronic as exposure increases to rotary wing flight conditions [2]. Laboratory studies have shown that back muscles respond strictly proportional to vertical (z-axis) WBV at the frequency range produced by helicopter rotors [14], [15].

Prolonged exposure to WBV may cause permanent physical damage that affects the lower spinal region. The most damaging frequencies are those that are the resonance frequencies of the spinal column. Figure 1 illustrates the vibration resonance for the spinal column, occurring between 10 and 12 Hertz [3].

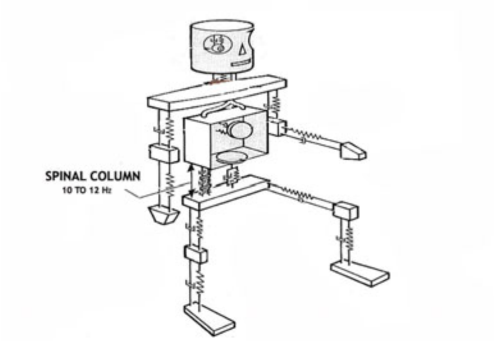

Figure 1: Mechanical spring model illustrating resonance frequencies of the spinal column

Current (2005) self-reported injuries from front-line aviators include suffering from significant numbness and pain in their lower-backs and legs after long flights. HSC-28 released a Hazard Report (HAZREP) on 5 April 2005 while conducting Amphibious Search and Rescue missions during seven days of extensive work-ups with the Kearsarge Expeditionary Strike Group (ESG). Approximately four hours into a seven-hour mission, both pilots experienced severe middle and lower back pain, which progressed to numbness and tingling sensations in their feet. After landing, both pilots experienced difficulty exiting the aircraft due to poor circulation in their lower extremities. Both aviators experienced severe back pain several hours later while trying to sleep. Evidence shows that insufficient seat pan cushioning causes a pinching of the sciatic nerve. This results in the legs becoming numb followed by paraesthesia (tingling sensation). In addition, a lack of lumbar support in the seat cushion leads to spinal support muscle fatigue. These factors contribute to increased stresses upon the T-12 to S-1 vertebrae due to muscle fatigue, causing pain and stiffness in the short-term, and misalignment and improper tracking of vertebrae in the long-term [18]. Increased mission lengths amplify the pain, stiffness, and general discomfort experienced by MH-60S pilots, forcing aircrews to deal with significant human factors. Physical discomfort in the cockpit naturally leads to inattention and distraction, both of which are human factors that can significantly contribute to poor decision-making[17]. If preventive measures are not taken, such a condition can result in spinal disk slippage [8]. This is not only incredibly painful and expensive to treat, but results in a significant number of lost workdays.

A HAZREP released in 2005 reported two pilots had to be carried out of their seats after flying in the MH-60S for 6+ hours. Another HAZREP released by HC-5 on 25 January 2005 formally reported that back and leg pain began two to four hours into flight and increased with time. Pilots reported that they were distracted and constantly shifting in their seats trying to get comfortable. Crews reported that after flying a full day, approximately ten hours, the pain took several hours to subside or in some cases lasted one to two days after landing.

> "*We have identified a "why" before it has resulted in a mishap or even a near miss. The number of pilots who have reported decreased situational awareness due to discomfort is concerning. In conjunction with the 50 percent mishap reduction campaign, we have been trying to identify human factors that could cause a mishap. This is a prime opportunity to fix the problem before we lose an asset.*"
>
> HC-5 Commanding Officer

The current seat cushions are only one-inch thick and provide little lumbar support. The 2003 Aviation Life Support System's (ALSS) Operator Advisory Group (OAG) listed seat endurance as the number two priority. Their application would increase endurance, reduce transmitted vibration, and enhance operational effectiveness. These commercial off-the-shelf (COTS) systems are available but not yet qualified for United States Naval (USN) aircraft systems. Evidence from flight clearance requests, Juge Advocate General (JAG) Investigation, HAZREPS, and personal experience suggest that pilots have resorted to looking for alternative solutions and in some cases have introduced their own unapproved seat cushion modifications at the potential cost of safety. Per a JAG Investigation report a Class A mishap reported an unauthorized seat cushion as one of two probable causal factors in the fatality of a tactical fleet aviator who failed to initiate ejection. The makeshift seat pad could have obstructed the Mishap Pilot's (MP) ejection handle, making a timely ejection impossible or the MP made a conscious decision not to eject. [Information obtained through the Freedom of Information Act.]

Recommended occupational exposure criteria were developed to prevent spinal injuries and minimize the risk of fatigue and discomfort [1], [10]. Self reported symptoms and the incidence of medical problems as well as measured exposures were consistent with effects of exposures in excess of recommended criteria. Therefore, in addition to evaluating current equipment, modified seat cushions designed to have lower vibration levels were also evaluated. This study evaluated WBV exposure of MH-60S pilots for the current seat cushion and two anti-vibration seat cushions.

Methods

A triaxial seat pad accelerometer, as shown in Figure 2, was used to measure vibration acceleration levels for the current and anti-vibration seat cushions' (A & B) in the X, Y, and Z-axes of direction, as shown in Figure 3. These three accelerometers were incorporated into one unit, encased in an instrumented hard rubber disc, placed on the top of the current and anti-vibration seat cushions under the pilots' buttocks during helicopter operations. The sensitivities of the accelerometers were within 10% of each other as required by International Standards Organization (ISO) 2631, Part I [10] and the American Conference of Governmental Industrial Hygienists (ACGIH) [1]. The triaxial seat pad accelerometers were affixed to the seat using tape uniformly.

Figure 2: Triaxial Seat Pad

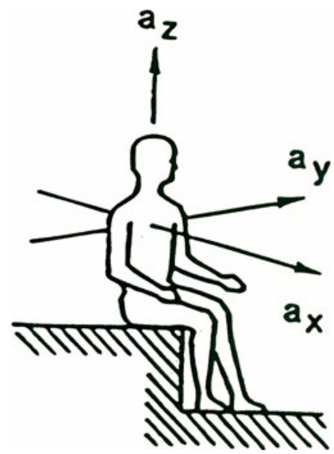

Figure 3: Biodynamic Coordinate System

The acceleration levels for the current and anti-vibration seat cushions were averaged in 5-minute intervals for several straight and level flights, recorded using the SVAN 948 vibration meter/frequency analyzer (shown in Figure 4), and compared.

Figure 4: Frequency Analyzer/Vibration Meter

The data was then uploaded to a computer using SVANTEK software. The results for each seat cushion were superimposed on the ACGIH Threshold Limit Values' (TLV) WBV time-dependent curves. The Z-axis curves depicted in Figure 5 indicate the allowable time of exposure to vibration acceleration levels dependent on the frequency in which the vibration occurs. The curves account for the human vibration resonance that occurs in the four to eight Hz frequency range with respect to the Z-axis. Because most of the reported injuries were spine-related, the vibration levels at the most damaging frequencies to the spinal column, 10-12 Hertz were analyzed. There are similar acceleration TLV curves for the X and Y-axes that consider human vibration resonance occurring in the one to two Hz frequency range.

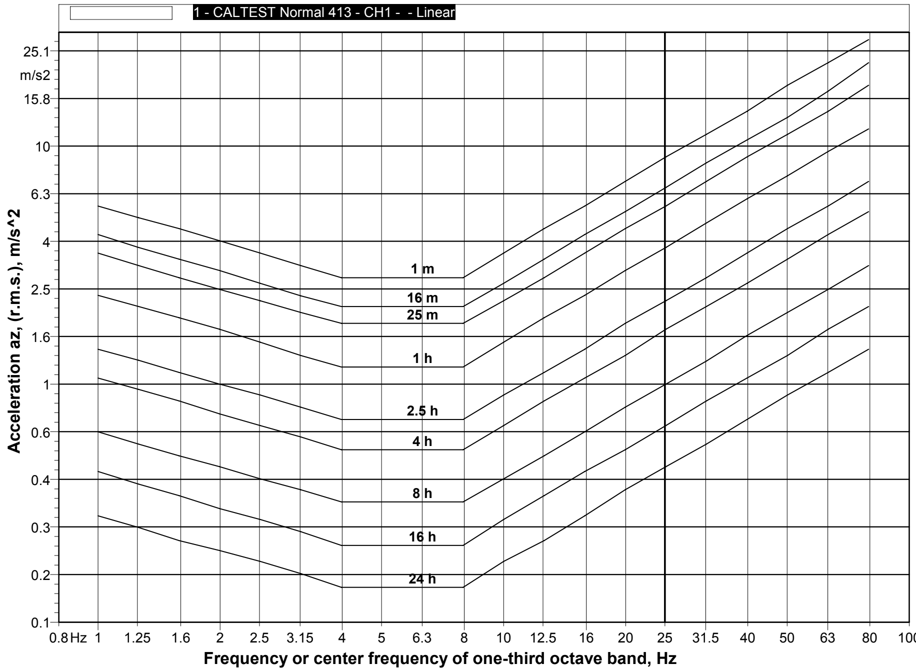

Figure 5: Longitudinal Acceleration TLVs as a function of frequency and exposure time. Based on *Threshold Limit Values and Biological Exposure Indices for 2004* by the ACGIH.

Results and Discussion

According to the ACGIH TLVs [1], the axis with the highest spectral peak intersecting the curve with the shortest exposure time dominates and determines the permissible exposure. In evaluating the data collected, it was apparent that this occurred at 16 Hz for the Z-axis data. The graphical display of the Z-axis spectral mean acceleration values is shown in Figure 6.

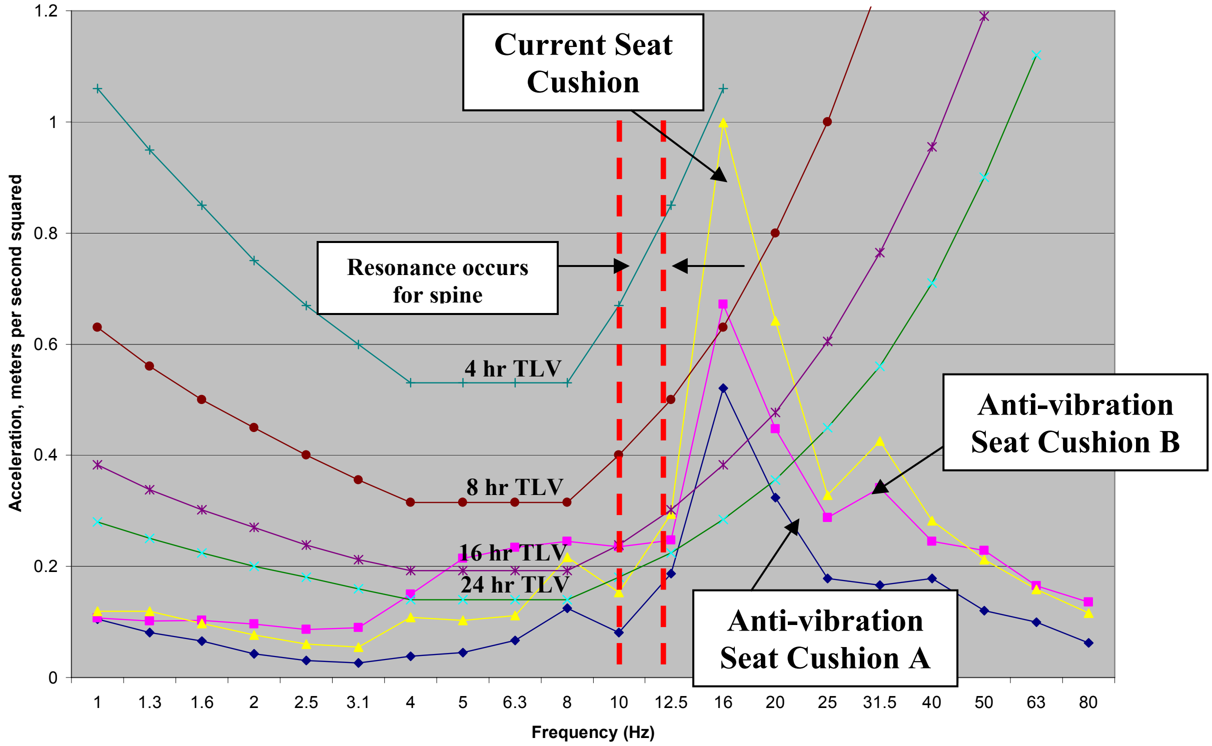

Figure 6: Mean acceleration values of the current and anti-vibration seat cushions A and B in the Z-axis and the applicable ACGIH threshold limit values.

The mean acceleration value at 16 Hz in the Z-axis indicates that exposure time should not exceed 6 hours for the current seat cushion and 8 hours for anti-vibration seat cushion B. The exposure time for anti-vibration seat cushion A should not exceed 16 hours. Therefore, anti-vibration seat cushion A outperformed the current seat cushion and anti-vibration seat cushion B by exhibiting significantly reduced vibration levels. Additionally, the current seat cushion and anti-vibration seat cushion B reached the 16 hour exposure limit curve at resonance (most damaging frequency range) for the spinal column, whereas the anti-vibration seat cushion A did not even reach the 24 hour exposure limit curve at resonance for the spinal column. The *t*-test at 16 Hz showed that the mean acceleration values for the current and anti-vibration seat cushions were significantly different in the Z-axis. The statistical analysis results for the Z-axis are shown in Table 1.

Seat Cushion	**Mean Acceleration (m/s^2)**	**Standard Deviation (m/s^2)**
Current Seat Cushion	0.998	0.386
Anti-vibration Seat Cushion A	0.530	0.160
Anti-vibration Seat Cushion B	0.668	0.178
t-value = 2.65	p-value = <0.005	Degrees of freedom = 175

Table 1: Statistical summary and results of the one-tailed t-test of the current and anti-vibration seat cushions in the Z-axis at 16 Hertz

The number of measurements was a limiting factor due to the allotted 15 flight hours for each anti-vibration seat cushion as stipulated by the flight clearance for testing purposes.

Process Risk Evaluation by System Safety Criteria

Application of the system safety process of Military Standard 882 [11] is required for system acquisition and facility support by DoD and Navy regulations [4], [12], [13]. DoDI 5000.2 [4] requires life cycle risk management[1]. The risk review and acceptance criteria of DoDI 5000.2 were correlated with the personnel exposures measured before and after intervention. Mishap severity categories and probabilities shown in Tables 2 and 3 were used to provide consistency with DoD and Navy guidance for use of Military Standard 882. [11], [12],[13].

Table 2. Suggested Mishap Severity Categories

Category	Description	Environmental (E)[1]	Safety (S)[2]	Occupational Health (OH)[3]
I	Catastrophic	Irreversible severe damage in violation of law or damage > $1M	Death, permanent total disabling injury, or loss/damage > $1M	Dose of a substance or induced stress levels leading to death or a permanent total disabling illness
II	Critical	Reversible damage in violation of law or damage > $200K < $1M	Partial disabling injury, and/or ≥ 3 people hospitalized, equipment/property loss/damage > $200K < $1M	Dose of a substance or induced stress levels leading to permanent partial disabling illness, and/or ≥ 3 people hospitalized
III	Marginal	Reversible damage, no violation of law, damage > $10K < $200K	Non-fatal injury, 1 or more lost work days, equipment/property loss/damage > $10K < $200K	Dose of a substance or induced stress levels leading to illness with 1 or more lost work days
IV	Negligible	Minimal damage, no violation of law	Non-fatal injury, no lost work days, equipment/property loss/damage > $2K < $10K	Dose of a substance or induced stress levels with no lost work time and no job impairment

[1] **Environmental (E)** - Hazards in terms of damage to the natural environment. *Dollar values include fines, legal fees, cleanup, restoration, etc.
[2] **Safety (S)** - Hazards in terms of equipment/property loss/damage, death/injury. *Dollar values include replacement/ repair costs.
[3] **Occupational Health (OH)** - Hazards in terms of dosage (e.g., concentration vs. time) of a substance or induced loads (e.g., heat, cold, shock).

Table 3. Suggested Mishap Probability Levels

Category	Description	Fleet of Systems[1]	Individual System
A	Frequent	Continuously, P=1	Frequently, $10^{-1} < P < 1$
B	Probable	Continuously, $10^{-1} < P < 1$	Several times, $10^{-3} < P < 10^{-1}$
C	Occasional	Several times, $10^{-3} < P < 10^{-1}$	Sometimes, $10^{-6} < P < 10^{-3}$
D	Remote	Sometimes, $10^{-6} < P < 10^{-3}$	Unlikely, $P < 10^{-6}$
E	Improbable	Unlikely	Unlikely

[1] The expected size of the fleet or inventory should be defined prior to accomplishing an assessment of the system.
Environmental (E) - Probability of adversely impacting natural environment over the system's life cycle.
Safety (S) - Probability of incurring a human loss over the system's life cycle.
Occupational Health (OH) - Probability of exposing crew, work force, or public over the system's life cycle.

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[1] DoDI 5000.2 Operation of the Defense Acquisition System May 12, 2003 Paragraph 3.9.2 Sustainment Effective sustainment of weapon systems begins with the design and development of reliable and maintainable systems through the continuous application of a robust systems engineering methodology. As a part of this process, the PM shall employ human factors engineering to design systems that require minimal manpower; provide effective training; can be operated and maintained by users; and are suitable (habitable and safe with minimal environmental and occupational health hazards) and survivable (for both the crew and equipment).

Table 4 illustrates the mishap risk assessment used, while Table 5 correlates the risk matrix to required levels of management acceptance with regard to hazard level on the basis of probability and severity.

Table 4. Mishap Risk Assessment Matrix

Probability (Frequency)	Severity			
	I Catastrophic	II Critical	III Marginal	IV Negligible
A Frequent	IA – 1	IIA – 3	IIIA – 7	IVA – 13
B Probable	IB – 2	IIB – 5	IIIB – 9	IVB – 16
C Occasional	IC – 4	IIC – 6	IIIC – 11	IVC – 18
D Remote	ID – 8	IID – 10	IIID – 14	IVD – 19
E Improbable	IE – 12	IIE - 15	IIIE - 17	IVE - 20

Table 5. Mishap Risk Categories and Mishap Risk Acceptance Levels *

Mishap Risk Index (MRI)	Category	Mishap Risk Waver Authority
1-5	High Risk	Requires Service Acquisition Executive (CAE (ASN-RDA) USSOCOM) Approval.
6-9	Serious Risk	Requires Program Executive Officer (PEO) Approval
10-17	Medium Risk	Requires Program Manager Approval
18-20	Low Risk	Requires Program Manager Review

* (DoDI 5000.2 and SECNAVINST 5000.2C, Derived from Military Standard 882D)

Table 6. Mishap Risk Assessment Matrix Applied to Current Mk V Vessels and Prospective Future Designs Consistent with Recommended (CDD) Acquisition Criteria

Probability (Frequency)	Severity			
	I Catastrophic	II Critical	III Marginal	IV Negligible
A Frequent	IA – 1	IIA – 3	IIIA – 7	IVA – 13
B Probable	IB – 2	IIB – 5	**IIIB – 9**	IVB – 16
C Occasional	IC – 4	**IIC – 6**	IIIC – 11	**IVC – 18**
D Remote	ID – 8	IID – 10	**IIID – 14**	IVD – 19
E Improbable	IE – 12	IIE – 15	IIIE - 17	IVE – 20

Initial risk level IIB to IIIB, depending upon length of exposure

5	**High Risk**	**Requires Service Acquisition Executive (CAE (ASN-RDA) USSOCOM) Approval.**
9	**Serious Risk**	**Requires Program Executive Officer (PEO) Approval**

Modified risk level IIIC or IIID, somewhat dependent on length of exposure.

11	**Serious Risk**	**Requires Program Executive Officer (PEO) Approval (Recommended CDD threshold)**
14	**Low Risk**	**Requires Program Manager Review (Recommended CDD Objective)**

Risk Evaluation of WBV and Postural Discomfort in Flight

Evaluation of risks associated with poorly controlled vibration levels in MH-60S aircraft suggests a probable (> 0.1) or occasional (> 0.01) exposure to missions in which vibration levels exceed recommended WBV criteria. Postural discomfort is amplified by designs that fail to accommodate the anthropometric measurements that accommodate 90% of the population (5% female; 95% male). Direct impacts appear consistent with mishap severity category III (marginal) long-term effects on WBV relating to leg and back discomfort. This would be consistent with IIIC (Program Executive Officer) or IVB/C (Program Manager) associated criteria for risk acceptance. However, an additional level of human and programmatic risk must be considered if discomfort impairs mission endurance and/or increases the likelihood of pilot error during mission operations. Note that in-flight mission situations deteriorate rapidly in the presence of WBV that may be significant enough to impair situational awareness.

Crashworthiness and personnel survivability criteria require impact resistance of up to 19 gs. The current seating systems meet crashworthiness standards, but were not designed to attenuate WBV. Improved conformance to anthropometric measurements of pilots poses a concurrent challenge. However, acquisition requirements must strive to meet these concurrent challenges to support increasing demands for mission endurance and accommodate 90% of the general population. Updated criteria for Capability Development Documents (CDDs) and Capability Production Documents (CPDs) with appropriate thresholds (minimum desired performance) and objectives (optimal performance) should be developed. Aircrew system design must consider the need for programmatic support for technology development and testing. Resource sponsors should consider initiating program requirements and budget justification (POM process) to support Research, Development, Test, and Evaluation (RDT&E) and eventual procurement of best available equipment.

Conclusions

The results of the helicopter seat cushion study showed that pilots of the MH-60S could operate the helicopter with the current seat cushion for less than 6 hours and the anti-vibration seat cushion B for approximately 8 hours without being overexposed to WBV. Since the average flight during a deployment or mission could last up to 8 hours, the current exposure places the pilots at an unacceptable risk of injury, lack of mission readiness, and possible equipment damage. In the future, helicopters will be outfitted with auxiliary fuel tanks, which means fewer refuels with be required per mission. This may extend a pilot's overall sitting time.

At this point, the longevity of the anti-vibration seat cushions A and B is unknown and should be evaluated for a longer duration by the fleet. It appears that anti-vibration seat cushion B is not as durable as anti-vibration seat cushion A.

The anti-vibration seat cushion A increased the stay-time to approximately 16 hours. In order to lower the pilots' exposure to WBV and reduce potential safety mishaps, it is recommended that the current MH-60S's be retrofitted with the anti-vibration seat cushion A.

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Additional Information

Additional information on vibration exposure and its relevance to safety in the acquisition process is available on the Naval Safety Center website at www.safetycenter.navy.mil/acquisition.

Biography

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